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Kneading sequences for symmetric PL bimodal maps

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1 PL bimodal map

PL bimodal maps are the piecewise linear maps on the interval with three monotone segments. We consider the family of symmetric bimodal maps on the interval $[-1, 1]$, which map -1 and 1 to -1 and 1 respectively. A bimodal map has two turning points t_1 and t_2 on $(-1, 1)$. The map is strictly increasing on $[-1, t_1]$ and on $[t_2, 1]$, and strictly decreasing on $[t_1, t_2]$. Such maps are called $\{+ - +\}$ type bimodal maps. Let λ be the slope on the first and third segments, and $-\mu$ be that on the second segment ($\lambda, \mu > 0$).

The map is given by the formula

$$F_{\lambda, \mu}(x) = \begin{cases} \lambda x + \lambda - 1 & (x \leq t_1) \\ -\mu x & (t_1 \leq x \leq t_2) \\ \lambda x - (\lambda - 1) & (x \geq t_2) \end{cases}$$

where $t_1 = -t_2 = \frac{1 - \lambda}{\lambda + \mu}$. The parameters λ and μ are chosen from the set

$$D = \{(\lambda, \mu) : \lambda > 1, \mu > 1, \frac{2}{\lambda} + \frac{1}{\mu} \geq 1\}.$$

Since the maps are bimodal and symmetric at the origin, $t_1 < 0$. Therefore $\lambda > 1$. If $\mu < 1$ then there exists an attracting fixed point. If $\mu = 1$ then $x \in [t_1, t_2] \setminus \{0\}$ is 2-periodic. Therefore the condition $\mu > 1$ is necessary for topological entropy to be positive. The last condition $\frac{2}{\lambda} + \frac{1}{\mu} \geq 1$ is required for the existence of an F -invariant interval.

Lemma 1.1 *Assume that $\lambda, \mu > 1$. There exists an interval whose interior is invariant under F , if and only if $\frac{2}{\lambda} + \frac{1}{\mu} \geq 1$.*

If $\frac{2}{\lambda} + \frac{1}{\mu} < 1$, then the invariant interval is a Cantor set. In this case, topological entropy is $\log 3$.

Now we consider another set of the parameters λ and μ

$$D_0 = \{(\lambda, \mu) \in D : \frac{1}{\lambda} + \frac{1}{\mu} < 1\}.$$

For $(\lambda, \mu) \in D \setminus D_0$ there exists an F -invariant interval, such that F maps the negative points and the positive points to positive points and negative points respectively.

Lemma 1.2 *For $(\lambda, \mu) \in D$, we have $F_{\lambda, \mu}^2(t_1) > 0$, if and only if $\frac{1}{\lambda} + \frac{1}{\mu} < 1$.*

2 Symbolic dynamics for the bimodal maps

2.1 Kneading sequences

We consider kneading sequences adapted to a special case of bimodal maps that are symmetric at the origin. Let f be a $\{+ - +\}$ type bimodal map with two turning points $t_1 < 0$ and $t_2 > 0$. Let f^n is the n th iterate of f . The **orbit** of $x_0 \in [f(t_2), f(t_1)]$ is

$$\begin{aligned} O(x_0) &= (x_0, f(x_0), f^2(x_0), \dots) \\ &= (x_0, x_1, x_2, \dots). \end{aligned}$$

Its **itinerary** is

$$I(x_0) = (A_0 A_1 A_2 \dots),$$

where

$$A_i = \begin{cases} L & (f(t_2) \leq x_i < t_1) \\ C_L & (x_i = t_1) \\ M & (t_1 < x_i < t_2) \\ C_R & (x_i = t_2) \\ R & (t_2 < x_i \leq f(t_1)). \end{cases}$$

The itineraries $K_L(f), K_R(f)$ for the critical values $f(t_1), f(t_2)$ are called the **kneading sequences** of the map:

$$K_L(f) = I(f(t_1)), K_R(f) = I(f(t_2)).$$

For the itinerary $I(x_0) = (A_0 A_1 A_2 \dots)$, we denote the number of i 's such that $A_i = M$ (for $i < n$) by θ_n , and let $\varepsilon_n = (-1)^{\theta_n}$. We denote a symbol by a capital letter without underline and a sequence by a capital letter with underline.

We define an order on the symbols and the sequences as follows.

- (i) $L < C_L < M < C_R < R$.
- (ii) let $\underline{S} = (A_0 A_1 A_2 \dots)$ and $\underline{T} = (B_0 B_1 B_2 \dots)$ be two different sequences. Let k be the smallest non-negative integer with $A_k \neq B_k$. We say $\underline{S} < \underline{T}$ if $A_k < B_k$ and $\varepsilon_k = 1$ or if $A_k > B_k$ and $\varepsilon_k = -1$ for the above k .

For $x, y \in [f(t_2), f(t_1)]$, it follows that

- (i) if $I(x) < I(y)$ then $x < y$.
- (ii) if $x < y$ then $I(x) \leq I(y)$.

$|\underline{A}|$ denote the cardinality of \underline{A} . When $|\underline{A}| = 0$, we write $\underline{A} = \phi$. If $|\underline{A}| > 0$, then $\underline{A} > \phi$.

For $\underline{A} = (A_0 A_1 A_2 A_3 \dots)$, define the **shift operator** σ by

$$\sigma(\underline{A}) = \begin{cases} \phi & \text{if } \underline{A} = C_L, C_R \text{ or } \phi \\ (A_1 A_2 A_3 \dots) & \text{otherwise} \end{cases}$$

We call a sequence \underline{A} **maximal** if $\sigma^k(\underline{A}) \leq \underline{A}$ for $k = 1, 2, \dots$. The kneading sequence $K_L(f)$ is maximal.

2.2 The products of the sequences

We say a sequence \underline{A} is **even** or **odd** according to the parity of the number of M 's it contains. We shall write \underline{AB} for the concatenation of \underline{A} and \underline{B} , and $\underline{A}^n = \underline{A} \cdots \underline{A}$ (n times) and $\underline{A}^\infty = \underline{AA} \cdots$. Let $\underline{A} \neq \phi$ and $\underline{B} \neq C_L$ or C_R . We define $\bar{\underline{A}}$ as follows:

$$\bar{\underline{A}}_i = \begin{cases} R & (A_i = L) \\ C_R & (A_i = C_L) \\ M & (A_i = M) \\ C_L & (A_i = C_R) \\ L & (A_i = R) \end{cases}$$

We define ***-product** and ****product** as follows :

(i) if \underline{A} is even

$$\underline{A} * B_0 B_1 \cdots = \underline{A} B_0 \underline{A} B_1 \cdots$$

(ii) if \underline{A} is odd

$$\underline{A} * B_0 B_1 \cdots = \underline{A} \check{B}_0 \underline{A} \check{B}_1 \cdots$$

where

$$\check{B}_i = \begin{cases} M & (B_i = L) \\ L & (B_i = M) \\ R & (B_i = R) \end{cases}$$

(iii) if \underline{A} is even

$$\underline{A} ** B_0 B_1 \cdots = \underline{A} B_0 \bar{\underline{A}} B_1 \cdots$$

(iv) if \underline{A} is odd

$$\underline{A} * B_0 B_1 \dots = \underline{A} \check{B}_0 \bar{A} \hat{B}_1 \dots$$

where

$$\check{B}_i = \begin{cases} L & (B_i = L) \\ R & (B_i = M) \\ M & (B_i = R) \end{cases}$$

$$\hat{B}_i = \begin{cases} M & (B_i = L) \\ L & (B_i = M) \\ R & (B_i = R). \end{cases}$$

Let \underline{A} be maximal. We say \underline{A} is **primary** if it cannot be written as $\underline{B} * \underline{D}$ or $\underline{B} * * \underline{D}$ with $\underline{B} \neq \phi$ and $\underline{D} \neq \phi$.

There are some kneading sequences $K_L(f)$ that contain the symbol C_L . These sequences can be written $(\underline{A}C_L)^\infty$ or $(\underline{A}C_R\bar{A}C_L)^\infty$ by using a sequence $\underline{A} \neq \phi$. These sequences satisfy the following inequalities :

$$\begin{aligned} \underline{A} * L^\infty &< \underline{A}C_L < \underline{A} * ML^\infty \\ \underline{A} * * M^\infty &< \underline{A}C_R\bar{A}C_L < \underline{A} * * RM^\infty \end{aligned}$$

Proposition 2.1 *Let $\underline{A}C_L$ be maximal. If $\underline{A} * L^\infty \leq K_L(f) \leq \underline{A} * ML^\infty$ then there is a \underline{B} such that $K_L(f) = \underline{A} * \underline{B}$. This \underline{B} is maximal.*

Proof. Put $n = |\underline{A}C_L|$. Assume that \underline{A} is even. We first show that

$$\underline{A} * L^\infty \leq \sigma^n(K_L(f)) \leq \underline{A} * ML^\infty. \quad (1)$$

Our assumptions implies

$$(\underline{A}L)^\infty \leq K_L(f) \leq \underline{A}M(\underline{A}L)^\infty.$$

Then we have $K_L(f) = \underline{A}B_0 \cdots$, where $B_0 = L, C_L$, or M . If $B_0 = L$ then $\sigma^n((\underline{A}L)^\infty) \leq \sigma^n(K_L(f))$. If $B_0 = M$ then $\sigma^n(\underline{A}M(\underline{A}L)^\infty) \leq \sigma^n(K_L(f))$. In both of the cases we have $(\underline{A}L)^\infty \leq \sigma^n(K_L(f))$. We get $\sigma^n(K_L(f)) \leq K_L(f)$ since $K_L(f)$ is maximal. Therefore we obtain the inequality (1). If $B_0 = C_L$, the inequality (1) holds since $\sigma^n(K_L(f)) = K_L(f)$.

By induction, for all $p \geq 1$

$$\underline{A} * L^\infty \leq \sigma^{np}(K_L(f)) \leq \underline{A} * ML^\infty.$$

Thus $K_L(f)$ is of the form $\underline{A}B_0X$. From the reasoning in the preceding paragraph, it follows that X must be again of the same form. Hence

$$K_L(f) = \underline{A}B_0\underline{A}B_1 \cdots = \underline{A} * \underline{B}.$$

In the case that \underline{A} is odd, we also have $K_L(f) = \underline{A} * \underline{B}$.

Next, we show that $\underline{B} = B_0B_1 \cdots$ is maximal. For that purpose it is enough to prove that $\sigma^k(\underline{B}) \leq \underline{B}$ for any k . Since $K_L(f)$ is maximal, it follows that for any k

$$\sigma^{kn}(\underline{A} * \underline{B}) \leq \underline{A} * \underline{B}. \quad (2)$$

We assume that for some \tilde{k}

$$B_k B_{k+1} \cdots B_{k+\tilde{k}-1} = B_0 B_1 \cdots B_{\tilde{k}-1} \quad (3)$$

and

$$B_{k+\tilde{k}} \neq B_{\tilde{k}}. \quad (4)$$

If \underline{A} is even, then from (2)

$$\underline{A}B_k \underline{A}B_{k+1} \cdots \underline{A}B_{k+\tilde{k}} < \underline{A}B_0 \underline{A}B_1 \cdots \underline{A}B_{\tilde{k}}$$

Since $\underline{A}B_k \underline{A}B_{k+1} \cdots B_{k+\tilde{k}-1} \underline{A} = \underline{A}B_0 \underline{A}B_1 \cdots B_{\tilde{k}-1} \underline{A}$, we obtain $\sigma^k(\underline{B}) < \underline{B}$. We also have the same inequality in the case \underline{A} is odd. If the assumption (3) (4) does not hold for any \tilde{k} , then \underline{B} is periodic with period k , i.e. $\sigma^k(\underline{B}) = \underline{B}$. ■

Lemma 2.2 Assume $\underline{A} * L^\infty \leq K_L(f) \leq \underline{A} * ML^\infty$. If $K_L(f) = \underline{A} * \underline{B}$ then $L^\infty \leq \underline{B} \leq ML^\infty$ and $\sigma(\underline{B}) \leq \sigma^k(\underline{B})$ for any $k \geq 1$.

Lemma 2.3 Assume $\underline{A} * L^\infty \leq K_L(f) \leq \underline{A} * ML^\infty$. If $\sigma^n(K_L(f)) \leq I(x) \leq K_L(f)$, then $\sigma^n(K_L(f)) \leq I(f^n(x)) \leq K_L(f)$, where $n = |AC_L|$.

Proposition 2.4 Let $\underline{A}C_R\bar{\underline{A}}C_L$ be maximal. If $\underline{A} ** M^\infty \leq K_L(f) \leq \underline{A} ** RM^\infty$ then there is a \underline{B} such that $K_L(f) = \underline{A} * \underline{B}$. This \underline{B} is maximal.

Lemma 2.5 Assume $\underline{A} ** M^\infty \leq K_L(f) \leq \underline{A} ** RM^\infty$. If $K_L(f) = \underline{A} * \underline{B}$ then $M^\infty \leq \underline{B} \leq RM^\infty$ and $\sigma(\underline{B}) \leq \sigma^k(\underline{B})$ for any $k \geq 1$.

Lemma 2.6 Assume $\underline{A} ** M^\infty \leq K_L(f) \leq \underline{A} ** RM^\infty$. If $\sigma^n(K_L(f)) \leq I(x) \leq K_L(f)$, then $\sigma^n(K_L(f)) \leq I(f^n(x)) \leq K_L(f)$, where $n = |AC_R|$.

2.3 The properties of kneading sequence for PL bimodal maps

Now we remember Lemma 1.2 that for $(\lambda, \mu) \in D_0$ we have $F_{\lambda, \mu}^2(t_1) > 0$. The map $F_{\lambda, \mu}(x)$ has a fixed point $x = 0$. The itinerary of this point is M^∞ . Therefore for $(\lambda, \mu) \in D_0$ $K_L(F_{\lambda, \mu}) > RM^\infty$.

Proposition 2.7 If $K_L(F_{\lambda, \mu}) > RM^\infty$, then $K_L(F_{\lambda, \mu})$ is primary.

Proof. Assume that $K_L(F_{\lambda, \mu}) = \underline{AB}$. Lemma 2.3 implies that there is a interval J such that $F_{\lambda, \mu}^n(J) = J$ for $n = |\underline{A}C_L|$. We can take $\{x | \sigma^n(K_L(F_{\lambda, \mu})) \leq I(x) \leq K_L(F_{\lambda, \mu})\}$ for the above J . Then we find $F_{\lambda, \mu}^n$ on the interval J is unimodal. Let κ and $-\nu$ ($\kappa, \nu > 0$) be the slopes of $F_{\lambda, \mu}^n(J)$. Let k be the total number of L 's and R 's in \underline{A} , so the number of M 's is $n - 1 - k$. If \underline{A} is even, then we get the slopes

$$\begin{aligned}\kappa &= (-\mu)^{n-1-k} \lambda^k \lambda \geq \lambda^2 \\ (-\nu) &= (-\mu)^{n-1-k} \lambda^k (-\mu) \leq -\lambda\mu\end{aligned}$$

respectively. If \underline{A} is odd, then

$$\kappa = (-\mu)^{n-1-k} \lambda^k (-\mu) \geq \mu^2$$

$$(-\nu) = (-\mu)^{n-1-k} \lambda^k \lambda \leq -\lambda\mu.$$

In both of the cases, we get $\frac{1}{\kappa} + \frac{1}{\nu} < 1$, since $K_L(F_{\lambda,\mu}) > RM^\infty$ implies $\frac{1}{\lambda} + \frac{1}{\mu} < 1$.

This contradicts the result in Misiurewicz-Visiñescu [2] that $\frac{1}{\kappa} + \frac{1}{\nu} > 1$ is necessary for the existence of an F -invariant interval for unimodal maps. ■

Proposition 2.8 *If $K_L(F_{\lambda,\mu}) > RM^\infty$, then $K_L(F_{\lambda,\mu})$ is primary.*

Theorem 2.9 *Let $K_L(F_{\lambda,\mu})$ be a maximal and primary sequence such that $K_L(F_{\lambda,\mu}) > RM^\infty$. There is ν such that $K(g_\nu) = K_L(F_{\lambda,\mu})$, where g_ν is the PL bimodal map with the slopes alternately $\nu, -\nu, \nu(\nu > 1)$.*

Proof. From the maximality and the primarity of $K_L(F_{\lambda,\mu})$ as well as Proposition 2.1, we have one of the inequalities $K_L(F_{\lambda,\mu}) < \underline{A} * L^\infty$ or $K_L(F_{\lambda,\mu}) > \underline{A} * ML^\infty$. We set

$$M_{F_{\lambda,\mu}} = \{\nu : K_L(g_\nu) < K_L(F_{\lambda,\mu})\}$$

and

$$P_{F_{\lambda,\mu}} = \{\nu : K_L(g_\nu) > K_L(F_{\lambda,\mu})\},$$

and we claim these are open. We show only that $M_{F_{\lambda,\mu}}$ is open, and we can prove that $P_{F_{\lambda,\mu}}$ is open in the same way. We put $n = |\underline{A}C_L|$, and assume that \underline{A} is even. We take $\nu \in M_{F_{\lambda,\mu}}$ with $K_L(g_\nu) = \underline{A}D_n D_{n+1} \cdots < K_L(F_{\lambda,\mu})$ such that D_n is not equal to the n th symbol of $K_L(F_{\lambda,\mu})$. If $D_n \neq C_L$ then it is obvious that $M_{K(F_{\lambda,\mu})}$ is open. If $D_n = C_L$ then $K_L(F_{\lambda,\mu}) > \underline{A} * ML^\infty$. In this case there exists s_0 such that $K_L(F_{\lambda,\mu}) > \underline{A}M\underline{A}L^{s_0} \cdots$. Thus the sets $\{\tilde{D} = \underline{A}M(\underline{A}L)^s : s > s_0\}$ and $\{\tilde{D} = \underline{A}L(\underline{A}L)^s : \text{for any } s\}$ are included in $M_{F_{\lambda,\mu}}$, and $M_{F_{\lambda,\mu}}$ is open. If \underline{A} is odd, we can also prove that $M_{F_{\lambda,\mu}}$ is open in the same way. ■

3 Monotonicity of topological entropy

In this section we consider the monotonicity of kneading sequences and that of topological entropy.

We define an order on a pair of the parameters.

- (i) We say $(\lambda_1, \mu_1) \leq (\lambda_2, \mu_2)$ if $\lambda_1 \leq \lambda_2$ and $\mu_1 \leq \mu_2$.
- (ii) We say $(\lambda_1, \mu_1) < (\lambda_2, \mu_2)$ if $(\lambda_1, \mu_1) \leq (\lambda_2, \mu_2)$ and either $\lambda_1 \neq \lambda_2$ or $\mu_1 \neq \mu_2$.

We denote the pair of $K_L(F_{\lambda, \mu})$ and $K_R(F_{\lambda, \mu})$ by $K(\lambda, \mu)$. We say $K(\lambda_1, \mu_1) < K(\lambda_2, \mu_2)$ if and only if $K_L(F_{\lambda_1, \mu_1}) < K_L(F_{\lambda_2, \mu_2})$ and $K_R(F_{\lambda_1, \mu_1}) > K_R(F_{\lambda_2, \mu_2})$.

Let $h(\lambda, \mu)$ be the topological entropy of $F_{\lambda, \mu}$.

Proposition 3.1 *Let $(\lambda_1, \mu_1), (\lambda_2, \mu_2) \in D \setminus D_0$. If $(\lambda_1, \mu_1) < (\lambda_2, \mu_2)$ then $h(\lambda_1, \mu_1) < h(\lambda_2, \mu_2)$.*

We can show this proposition applying the result of [2] that proved the monotonicity of the topological entropy for PL unimodal maps.

Let

$$D_1 = \{(\lambda, \mu) \in D_0 : RC_R LC_L < K_L(F_{\lambda, \mu}) < R(RL)^\infty\}.$$

We obtain a proposition about the monotonicity of kneading sequences as follows:

Proposition 3.2 *Let $(\lambda_1, \mu_1), (\lambda_2, \mu_2) \in D_0 \setminus D_1$. If $(\lambda_1, \mu_1) < (\lambda_2, \mu_2)$ then $K(\lambda_1, \mu_1) < K(\lambda_2, \mu_2)$.*

The proof of this proposition is given by an analytical estimation.

Theorem 3.3 *Let $(\lambda_1, \mu_1), (\lambda_2, \mu_2) \in D_0 \setminus D_1$. If $(\lambda_1, \mu_1) < (\lambda_2, \mu_2)$ then $h(\lambda_1, \mu_1) < h(\lambda_2, \mu_2)$.*

We can prove this theorem from Theorem 2.9 and Proposition 3.2.

Theorem 3.4 *For a constant c with $0 < c < \log(3)$, the iso-entropy curve given by $h(\lambda, \mu) = c$ is connected.*

We prove this theorem in [3].

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